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Miniature Distributed Filters for Software Re-configurable Radio Applications.

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ABSTRACT

Variable preselection filters will be an important component of any software re-configurable radio design. To be of practical use, such a filter should occupy a minimum of board area in any transceiver layout. Slow-wave filters are introduced and their essential electrical characteristics and miniaturisation advantages are outlined. It is shown that this filter architecture is easily tuneable. MEMS switches can be used to switch line lengths and thus cause the centre frequency of the filter to be altered. MEMS switching is a preferred tuning method because it eliminates the non-linearity introduced by conventional tuning elements. A technique for designing a capacitively loaded, split ring filter is presented and some simulation and measurement results are given. The possibility of pushing the second resonant frequency beyond twice the fundamental frequency is highlighted as a feature of slow-wave filters. This feature is shown to be of limited advantage with the architecture under discussion.

I. INTRODUCTION

Linearity and electronically tuneable filters have been identified as being crucial components in the development of a software re-configurable transceiver ([1], [2] and [3]).

It is the intention of this paper to focus on tuneable filters, whilst, at the same time addressing the linearity requirements of this subsystem.

II. FLEXIBILE FILTERS

Flexible filters are required to perform the image reject function in a re-configurable superheterodyne receiver. They are also required to suppress unwanted side-bands in a re-configurable superheterodyne transmitter. These two functions are closely related.

In an ideal re-configurable radio design, flexible filters would be able to tune to any part of the radio frequency spectrum. As a first step of an investigation into the design techniques required for such a filter, it was decided to set a more modest goal. This goal was to design a filter capable of performing a pre-select function over the DECT, GSM1800, UMTS bands. This part of the spectrum is shown in Figure 1. Superimposed on this diagram are the proposed characteristics of a tuneable preselect filter. The centre frequency of this filter will be able to be changed from 1.855 GHz to 2.155GHz in 100MHz steps. The bandwidth of the filter is set at 100MHz. This figure represents about a 5% bandwidth. 5% bandwidth is chosen because it is a moderate bandwidth, neither wide-band nor narrow-band, and therefore shouldn't present too many challenges in terms of the filter design.

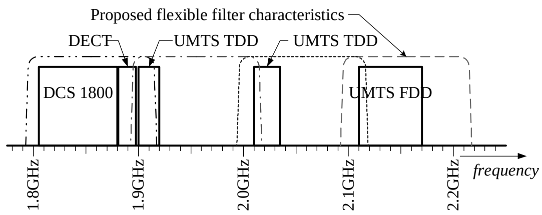

Figure 1 Spectrum occupied by major European air interface standards and the suggested performance of a tuneable RF filter to provide pre-selection.

Designing a tuneable filter to provide this filtering function is not straightforward. The first possibility that arises is tuning the filter via the use of varactor diodes. Varactor diodes are conventional P-N diodes designed to exhibit a change in capacitance as the DC voltage across the reverse biased junction changes (the capacitance decreases as the reverse voltage increases). Exploiting this change of capacitance to design a tuneable filter, has been dismissed at this juncture. It was felt that the non-linear nature of the varactor capacitance would lead to the resultant filter exhibiting a poor distortion performance (low Third Order Intercept) ([4]).

If varactor diodes are dismissed as a possible tuning mechanism and if it is assumed that the flexible preselect filter is to be made from passive distributed microwave components, then the remaining possibility is switching line lengths in and out of circuit.

III. APPLICATION OF MEMS TECHNOLOGY

During the last few years, the sophisticated techniques associated with the manufacture of integrated circuits, have begun to be adapted to manufacture mechanical systems on a microscopic scale. Such systems are referred to as MEMS or Micro Electro Mechanical

Systems. The most obvious electrical application of such a system is the MEMS switch[1]. It is envisage that a MEMS switch (see [5]) can be used to electrically alter the line lengths from which a filter is comprised. Because such a switch operates by making physical contact and not by utilising a semiconductor device such as a PIN diode or a FET, no distortion will be introduced.

IV. SLOW-WAVE FILTERS

Having decided to use switches to tune the preselect filter the question now is, "Are filter structures available that can be tuned by a simple switching arrangement?"

A family of filter structures referred to as "slow–wave" filters presents itself as being ideal for this application. Slow-wave filters have additional advantages. These advantages are:

- Miniaturisation of the filter structure.
- Shifting of the second resonance to a higher frequency.

A. Miniaturisation Issues

Before going on to discuss the tuning of slow–wave filters, we will initially consider the miniaturisation of planar filters. Conventional first steps taken to reduce distributed component size are as follows*:*

- Reduce the board height – this reduces track width in direct proportion to reduction in board height.
- Increase the dielectric constant of the board – this reduces line length, approximately[2] in proportion to the square root of the dielectric constant.

These techniques are a good first step, but there are other gains possible by "folding" the lines that make up the device. This folding process has a "spin off" in that it creates the possibility of using switches to "tune" the filter. The evolution of the capacitively loaded, split ring filter, which is one form of the slow-wave filter, is shown in Figure 2. It can be seen to result from a progressive "folding in" of the transmission line that makes up the filter. The structure eventually becomes a slow-wave filter when the line length becomes smaller than half a wavelength and open circuit coupled line provides capacitive loading at the ends of the line. References [8] and [9] discuss the design of this filter type.

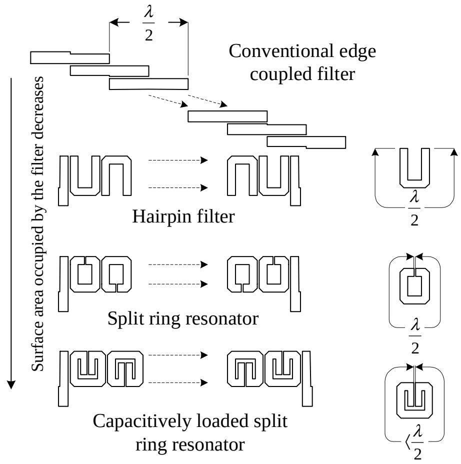

Figure 2 Evolution of the slow wave filter.

Variations on this theme are shown in Figure 3. The top two filters are edge coupled slow-wave filters (see [10] and [11]) whilst the bottom filter is an end coupled slow-wave filter (see [12]).

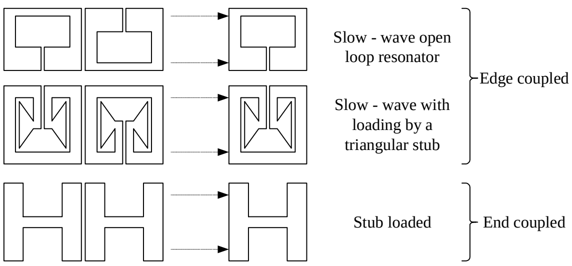

Figure 3 Alternative slow wave filter architectures

B. Analysis of Slow-wave filters

Essentially the resonator in a slow–wave filter can be viewed as a length of transmission line loaded at either end with a capacitive element. The equivalent circuit of such a filter is shown in Figure 4. These loading capacitance effectively introduce "dispersion" into the line. Dispersion means that the propagation constant of the line is frequency dependent, rather than being constant with frequency (as is the case with unloaded TEM lines).

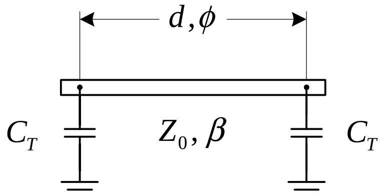

Figure 4 Equivalent circuit of line plus capacitive loading.

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[1] There are a number of other MEMS that may be used to provide a filter tuning action, for example interdigitated capacitors where the fingers are capable of mechanical movement relative to one another. References [6] and [7] provide an excellent introduction to this exciting development.

[2] In a microstrip line an electric field is present in the air above the line, as well is in the dielectric below it. Line length is proportional to the square root of the effective dielectric constant. The effective dielectric constant is a combination of the relative dielectric constant of the board with the relative dielectric constant of air (1).

It can be shown [10] that the first resonant frequency of a slow wave filter is given by:

$$\phi_{a0} = 2\tan^{-1}\left(\frac{1}{Z_0.\omega_0.C_T}\right) \qquad (1)$$

Where:

ϕ_{a0} = Electrical length of the transmission line at the fundamental resonant frequency.

Z_0 = The characteristic impedance of the transmission line.

C_T = The capacitive loading introduced by the coupled line.

ω_0 = The first resonant frequency of the line.

The second resonance has also been shown to occur when:

$$\phi_{a1} = 2.\pi - 2\tan^{-1}\left(\omega_1.Z_0.C_T\right) \qquad (2)$$

Where:

ϕ_{a1} = Electrical length of the transmission line at the second resonant frequency.

ω_1 = second resonant frequency.

Our filter design will be based on the capacitively loaded split ring filter shown in Figure 2. The capacitive loading introduced by the open circuit terminated coupled line is dependent on the odd order and even order impedance of this coupled line. The odd order impedance is important at the first resonance, where the voltages at each end of the line are out of phase. The even order impedance is important at the second resonance when the line resonates with voltages, at both ends of the line, in phase.

(1) and (2) can be rewritten in terms of the odd and even order impedances of the coupled lines as:

$$\phi_{a0} = 2.\tan^{-1}\left(\frac{Z_{0o}}{Z_0.\tan\theta_{0o}}\right) \qquad (3)$$

$$\phi_{a1} = 2.\pi - 2\tan^{-1}\left(\frac{Z_0.\tan\theta_{0e}}{Z_{0e}}\right) \qquad (4)$$

Where:

θ_{0o} = Odd order electrical length of the open coupled line.

θ_{0e} = Even order electrical length of the open coupled line.

Z_{0o} = Odd order characteristic impedance of the open coupled line.

Z_{0e} = Even order characteristic impedance of the open coupled line.

It is intended to tune the resonant circuit by line length changes introduced via MEMS switches. Figure 5 illustrates how this is to be achieved. Note that with all the transmission line lengths switched out of circuit that the resonator can revert to a split ring filter with only a small amount of capacitive loading (which occurs between the ends of the transmission line).

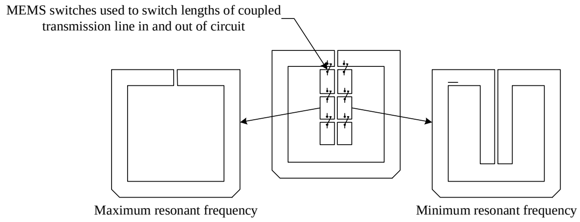

Figure 5 Proposed method of tuning the resonator.

C. *Design Procedure*

A filter based on a 4 pole low pass Chebyshev prototype, with 0.1dB pass band ripple, was designed, simulated and tested. The procedure used to design this filter was as follows.

(i) Design a coupled line, which can be folded into the resonator. Experience shows that an electrical length of about 25° is as much as can be used here. Design the coupled line to have an impedance of about 50Ω. Separate the odd order and even order impedances as much as possible, having regard to keeping the line widths and separation to manufacturable dimensions.

(ii) Calculate the length of transmission line required to resonate that line at the centre frequency of the lowest frequency filter that we intend to design. (3) can be used to do this

(iii) Design the physical layout of the resonator. Allow sufficient line lengths for corners.

(iv) Use an electromagnetic simulation package to plot coupling between the resonators as a function of the resonator separation ([12] and [13] are a good reference for this technique).

(v) With reference to conventional filter design tables (e.g. [14]) scale the information from the low pass prototype to calculate the impedance inverter gains required for the band pass design and the loaded Q at the input and output of the filter.

(vi) With the information from (iv) and (v) calculate the separation required of the resonators.

(vii) Calculate the required input and output tapping points for the filter given the loaded Q calculated in (v) using a technique outlined in [15].

(viii) The design is complete at this point and ready for checking via electromagnetic simulation.

(ix) The frequency of the second resonance can be calculated using equation (4). This is probably best done on a spread sheet noting that the LHS of equation (4) is the electrical length of the transmission line calculated in (ii) scaled up in frequency and the electrical length of the coupled line on the RHS is also scaled in frequency.

(x) Using equation (3) the lengths of the coupled lines to resonate the filter at frequencies higher than the minimum frequency can be calculated. Again, this is best done using an iterative technique on a spreadsheet. The approach again will be to find the frequency where the LHS of equation (3) matches the RHS.

V. RESULTS.

In order to test the feasibility of tuning the filter by shortening the length of the coupled line, filters designed to resonate at four separate centre frequencies were designed and simulated using the above technique.

The simulation program used was Agilent Technologies "Momentum RF". Results of the simulation are shown in Figure 6 (Momentum is an electromagnetic simulation package see [16]).

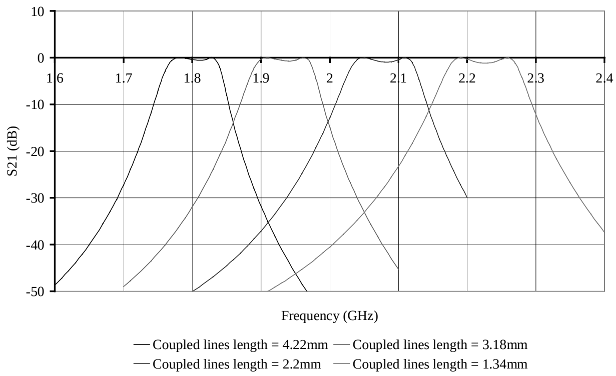

Figure 6 Simulated S_{21} versus frequency for the 4 filters.

It is thought that the difference between the simulated centre frequency, and the design centre frequency, is caused by the inability of the simple first order theory we are using, to account for a complex electromagnetic situation. At this juncture, no attempt has been made to bring the centre frequencies in to line with their target values. It is anticipated that this could be done by empirically shortening the resonator line lengths from their design values, and iterating the design, until the tuning was correct.

4 separate prototype filters were constructed These filters are shown in Figure 7.

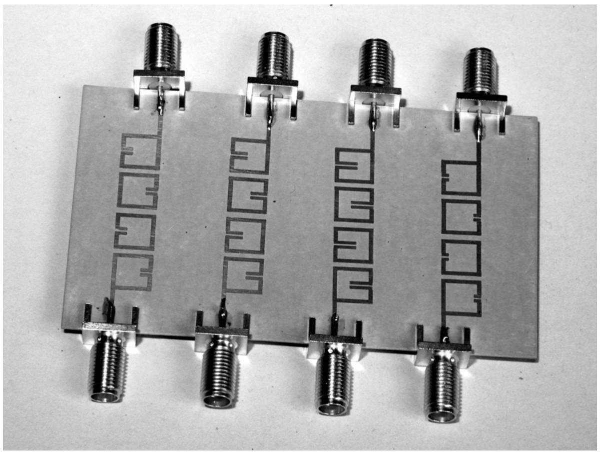

Figure 7 Prototype filters

The S parameters of these filters were measured on a Network Analyser. A combined plot of these measurements is given in Figure 8. Note that the pass band loss is of the order of 6dB, and there are errors in the centre frequency and "shape" of the filter. At this stage, it has to be assumed that these errors are due to the relatively crude techniques used to manufacture these filters.

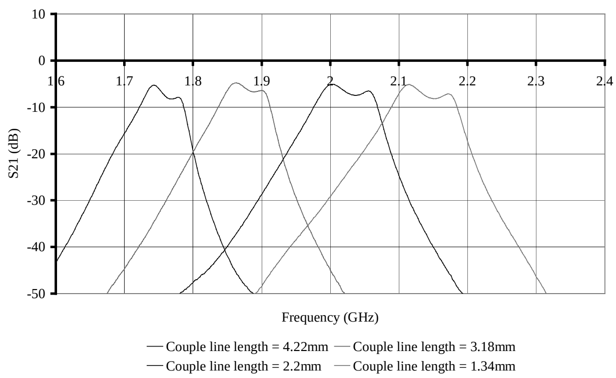

Figure 8 Measured S_{21} versus frequency for the 4 filters.

First and second resonant frequencies for all 4 filters were measured. Table 1 shows the results of this measurement. It can be seen that the second resonant frequency is not sufficiently different from twice the fundamental resonant frequency to cause the dispersion effect to be of much use using this architecture.

Coupled line length (mm)	Measured centre frequency at fundamental resonance (MHz)	Measured resonant frequency at 2^{nd} harmonic resonance (MHz)	ratio
4.22	1,763	3.813	2.163
3.18	1,888	4,025	2.132
2.2	2,038	4,250	2.085
1.34	2,150	4,388	2.041

Table 1 First and Second resonant frequencies

VI. CONCLUSION

A technique for miniaturising microwave RF filters has been discussed. Slow-wave filters are not only advantageous in producing physically small filters but they are also useful in being able to be tuned via a simple alteration of their physical layout. A prototype filter has been simulated and constructed. Pass band loss for the filters is about 6dB, which is close to what would reasonably be expected. Some more work needs to be done on the accurate prediction of filter centre frequency and bandwidth before a filter employing this technique combined with MEMS switches, can be constructed.

VII. ACKNOWLEDGEMENT

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VIII. ACRONYMS AND ABBREVIATIONS

FET	Field Effect Transistor
MEMS	Micro Electro Mechanical Systems
PIN	P type – Intrinsic – N type – Fast switching diode.
TEM	Transverse Electro Magnetic

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